

Searching for Millisecond Pulsars in Globular Clusters at Parkes: Further Results

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Abstract. We have discovered 12 new millisecond pulsars in 6 globular clusters in which no pulsars were previously known, in the first two years of a search at 1.4 GHz in progress at the Parkes radio telescope. Here we briefly describe the motivation, the new hardware and software systems adopted for this survey, and we present the results obtained thus far.

*Talk presented at the ACP Summer 2001 Workshop
“Compact Objects in Dense Star Clusters”
Aspen, 26 June 2001*

INTRODUCTION

Millisecond pulsars (MSPs) are formed in binary systems containing a neutron star (NS) which is eventually spun up through mass accretion from the evolving companion [1–3]. Despite the large difference in total mass between the disk of the Galaxy and the Globular Cluster (GC) system, about 50% of the entire MSP population has been found in the latter. This is not surprising because, apart from the evolution of primordial binaries, another formation channel for the MSPs is available in these stellar systems: exchange interactions in the ultra-dense stellar environment of the cluster core can sustain the formation of various kinds of binaries suitable for recycling neutron stars [4,5].

Many authors (e.g. [6–9]) have discussed the importance of the discovery of GC-MSPs as diagnostic tools for studying the dynamics of the clusters, the evolution of the binaries, the interstellar medium and the intracluster ionized gas [10] but, except for the significant case of 47 Tuc [11], the discovery rate of these objects strongly declined in the second half of the 1990s: in the 7 years from 1987 (when B1821–24 was discovered in M28 at Jodrell Bank [12]) to 1994 [13] 32 GC-MSPs entered the catalog, whereas no new source was published in the following 5 years.

Passing reasons (e.g. the upgrade of the Arecibo telescope) may have contributed to this trend, but a more meaningful explanation is that *searches for GC-MSPs are difficult because they are often distant pulsars in close binary systems*. Their large distances (*i*) make their fluxes typically very small and (*ii*) strongly distort their signals due to the dispersive effects of propagation through the interstellar medium. Their inclusion in tight binaries (*iii*) causes Doppler-shift changes of the apparent spin period and sometimes (*iv*) makes the radio signal periodically obscured by eclipses.

In the last couple of years a new search still in progress at the Parkes radio telescope has broken the hiatus in discoveries. In the following we review the current status of this experiment, including the preliminary announcement of two new clusters with which an MSP has now been associated [14].

OBSERVATIONS AND ANALYSIS

The availability of a new highly sensitive 20-cm receiver at Parkes together with a modern data acquisition system impelled us to undertake a new search of GCs for MSPs. This receiver has a system temperature of ~ 21 K and a bandwidth of ~ 300 MHz: performing long integrations ($\sim 1 - 2$ hr) we have been able to reach a very good nominal sensitivity (at signal-to-noise ratio $s/n=8$) of $\sim 100 - 150 \mu\text{Jy}$ for a typical 3 ms pulsar with dispersion measure $\text{DM} \sim 100 - 200 \text{ cm}^{-3} \text{ pc}$.

With the aim of improving our capability for probing distant clusters, we have designed and assembled at Jodrell Bank and Bologna a high resolution filterbank system consisting of 512×0.5 MHz adjacent channels per polarization. This enables us to minimize the deleterious effects of dispersion in the interstellar medium sufficiently to maintain significant sensitivity to MSPs with $\text{DM} \lesssim 300 \text{ cm}^{-3} \text{ pc}$.

We have selected about 60 clusters among the ones visible at Parkes according to their optical central density and satisfying the requirement $\text{DM}_{\text{exp}} \leq 300 \text{ cm}^{-3} \text{ pc}$ (where DM_{exp} is the DM expected for the cluster according to a model for the Galactic distribution of the ionized gas [15]): only a few of them contain already known MSPs. In order to reduce the probability of missing strong signals temporarily obscured by eclipse events we have performed multiple observations of each target cluster.

After adding the outputs of 1024 channels in polarization pairs, the resulting 512 data streams are each integrated and 1-bit digitized every $125 \mu\text{s}$: thus each observation produces a huge array, typically of $2 - 8$ Gbytes, requiring significant CPU resources for offline processing. In Bologna, we use a local cluster of 10 Alpha-500MHz CPUs and on occasion the Cray-T3E 256-processor system at the CINECA Supercomputing Center.

In the offline processing, each data stream is split into non-overlapping segments of 2100, 4200 or 8400 sec and these are processed separately. When no pulsar is known in a GC (and so the DM is unknown) the data are first de-dispersed over a wide range of $\sim 500 - 1000$ trial DMs, spanning the interval $\text{DM}_{\text{exp}} \pm 40\%$. Each de-dispersed series is then transformed using a Fast Fourier Transform. In the subsequent step, time-domain data are folded in sub-integrations using constant periods, each corresponding to a large number of spectral features above a given threshold. The resulting “sub-integration arrays” are searched both for a linear and for a parabolic shift in pulse phase. The linear correction is a consequence of having folded the data at an approximate spin period, whereas the parabolic correction is a signature of the acceleration of the source due to its orbital motion. Parameters for final pulse profiles with significant s/n are displayed for visual inspection.

This processing scheme gives some sensitivity for MSPs belonging to binary systems and most of our discoveries have been obtained using it. However, once a pulsar is detected and confirmed in a cluster, we usually reprocess the data de-dispersing them at the single DM value of the newly discovered pulsar; then the resulting time series undergoes a fully coherent search for “accelerated” signals over a large range of acceleration values. Being extremely CPU time-consuming, this kind of coherent search is not used when a DM value (or a narrow DM range) is not available.

Finally, in the case of two clusters (Liller 1 and Terzan 5, the latter containing 2 already known MSPs), we have established a collaboration with Scott Ransom, whose code [16] looks promising for detecting MSPs orbiting in ultra-close binaries, whose orbital period is shorter than the typical duration of an observation.

RESULTS TO DATE

So far we have discovered 12 new pulsars in 6 globular clusters, none of which had previously known pulsars associated with them. Seven of these pulsars are members of binary systems, and 6 of them have relatively high DM values. One pulsar follows a highly eccentric orbit and another one is eclipsed for a large fraction of the orbital period. Their preliminary parameters are reported in Table 1.

Table 1: PARAMETERS OF THE 12 NEW PSRs IN GCs

CLUSTER	PULSAR	Period (ms)	DM (cm ⁻³ pc)	P_b [†] (days)	a sin <i>i</i> [‡] (light-s)	M _c ^{min} [◇] (M _⊙)
NGC 6266	J1701–30A	5.241	114	3.80	3.48	0.19
	J1701–30B	3.593	114	0.14	0.25	0.12
	J1701–30C	3.806	114	0.21	0.19	0.07
NGC 6397	J1740–5340	3.650	72	1.35	1.66	0.19
NGC 6441	J1750–37	111.609	233	17.3 <i>e</i> =0.71	24.4	0.50
NGC 6522	J1803–30	7.101	192	single		
NGC 6544	J1807–2459	3.059	134	0.07	0.012	0.009
NGC 6752	J1910–59A	3.266	34	0.86	1.27	0.19
	J1910–59B	8.357	34	single		
	J1910–59C	5.277	34	single		
	J1910–59D	9.035	34	single		
	J1910–59E	4.571	34	single		

[†] = Orbital period

[‡] = Projected semi-major axis of orbit

[◇] = Minimum companion mass, assuming that the pulsar mass is 1.4 M_⊙

Five millisecond pulsars in NGC 6752

NGC 6752 is classified as a core-collapsed cluster with evidence of mass segregation [17]. Rubenstein & Bailyn [18] estimated a binary fraction for main sequence stars in the range 15%–38% inside the inner core radius ($< 11''$), decreasing to less than 16% beyond that. At least 6 dim X-ray sources have been identified on the basis of ROSAT pointings [19]. This is one of the clusters with the more precise distance measurement: $4.1 \text{ kpc} \pm 5\%$, obtained fitting the white dwarf (WD) sequence [20].

In this cluster we first discovered a 3.26 ms binary pulsar, PSR J1910–59A [21]. This pulsar has a relatively low $\text{DM} = 34 \text{ cm}^{-3}\text{pc}$, and scintillates markedly, similar to the pulsars in 47 Tuc. The orbital solution gives $P_b = 20.6 \text{ hr}$ and a minimum mass for the companion of $M_c^{\text{min}} = 0.19 M_\odot$ (assuming, as everywhere in this paper, that the pulsar mass is $1.40 M_\odot$). According to these parameters, it resembles a MSP+He-WD binary similar to those discovered in 47 Tuc [11,22].

Amplification due to scintillation helped in the detection of four additional MSPs in the same cluster (Table 1). All of them are isolated with spin periods in the range $4.6 - 9.0 \text{ ms}$.

Three binaries in NGC 6266

Another GC in which we have detected more than one MSP is NGC 6266. Its distance is estimated with the fitting of horizontal branch (HB) stars ($\sim 6.7 \text{ kpc}$ [23]), but the high level of reddening makes this measurement largely uncertain. It is classified as core-collapsed but with ambiguities [24]. Re-examining all the ROSAT pointings, Verbunt recently found a weak X-ray source, possibly interpreted as a quiescent soft X-ray transient [25].

The first MSP discovered here was PSR J1701–30A [21], with a spin period of 5.24 ms, an orbital period of 3.8 days, and a mass function indicating a minimum companion mass of $0.19 M_\odot$. Apart from the longer P_b this binary is similar to PSR 1910–59A, whereas the two other new systems, PSRs J1701–30B and J1701–30C, belong to the class of short-binaries with orbital periods of 3.8 hr and 5.2 hr (Table 1). The close orbit of PSR J1701–30B and the relatively high minimum companion mass cause significant variations of the acceleration term a during an observation. In this case, only the use of code developed at Bologna for searching both a and the derivative of the acceleration, da/dt , allowed the recovery of enough signal from this weak source at the confirmation stage (see Figure 1).

An ultra-compact binary in NGC 6544

NGC 6544 is one of the smallest GCs known: half of its mass is confined within 1.3 pc (at a distance of $\sim 2.6 \text{ kpc}$, measured by HB-star-fitting [26]). It displays the highest central luminosity density ($\rho_0 = 5.75$ in logarithm of solar luminosities per cubic pc) among the GCs having an associated pulsar (it ranks second among the entire GC population [24]).

The pulsar discovered, PSR J1807–2459 [21,16], has a fairly high flux density and was not detected in previous searches because of the relatively high $\text{DM} = 134 \text{ cm}^{-3}\text{pc}$. Timing performed at Jodrell Bank shows that it is part of an extremely compact binary, with an orbital period of only 1.7 hours (the second shortest known) and a projected semi-major axis of only $0.56 R_\oplus$. The corresponding minimum companion mass is only $0.009 M_\odot$ or about 10 Jupiter masses (the second smallest known) and the orbital separation is $(88/\sin i) R_\oplus = (0.8/\sin i) R_\odot$. If the orbital inclination angle i is small, this system could be similar to the close systems (MSP+WD or MSP+light not degenerate companion) seen in 47 Tuc [11], while if $i \sim 60^\circ$ (the a priori median of the possible inclinations) the companion could be a sub-stellar object: a brown dwarf or a planet.

Tape: GC0016 File: 9 Start Block: 1 Date: 000622 UT: 13:57:05.0000
 LST: 17:54:20.92 R.A.(J2000): 17:01:12.9920 Dec(J2000): -30:06:43.065
 Source: J1701-3006 Freq1(MHz): 1517.75000 512 x -0.5000 MHz Tsamp(ms): 0.125000

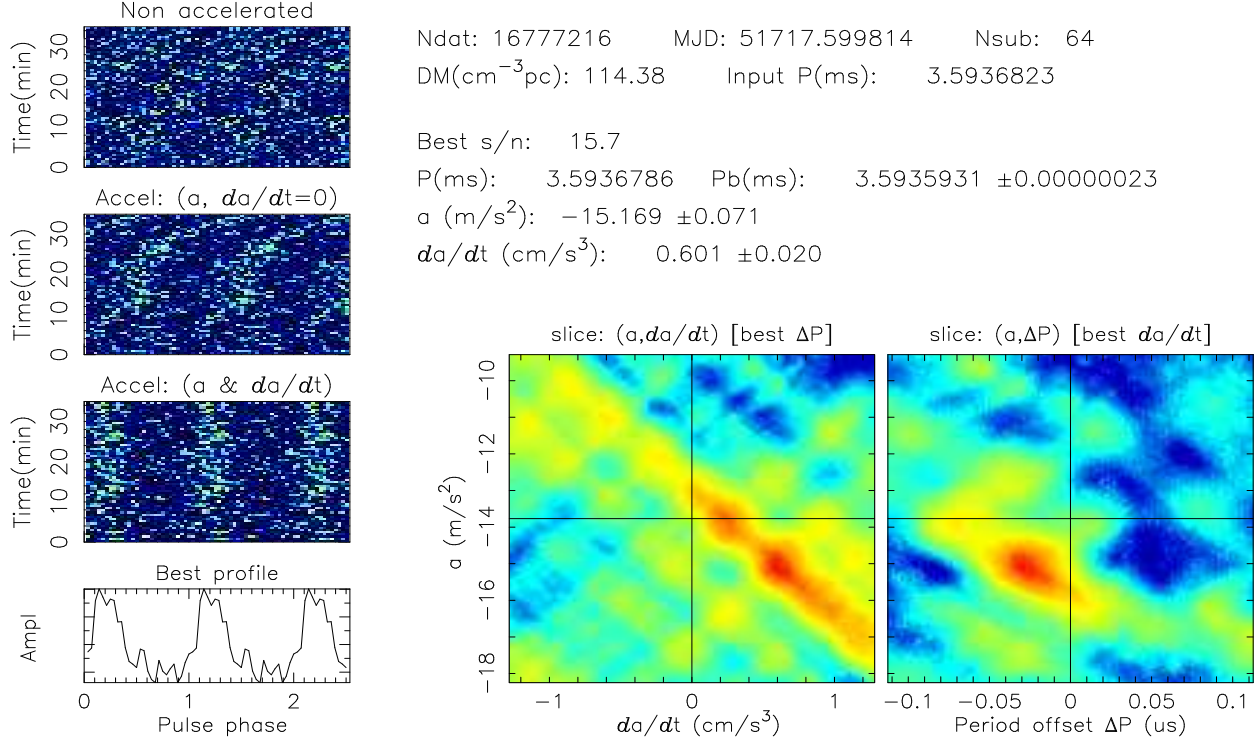


FIGURE 1. Confirming plot for PSR J1701-30B. In the upper left color panel is displayed the time-resolved signal from the source folding the 30-min data set at the nominal candidate spin period P and DM. The middle left panel shows the same signal after including a constant acceleration term a during the integration. The lower left color plot presents the time-resolved signal folded with the best values of a and da/dt . After these corrections, the pulse profile is easily recognizable (panel labeled with *Best profile*) with a good $s/n=15.7$. The two square panels in the lower section of the figure contain color-scale confidence plots for the three parameters searched: a , da/dt and the period offset ΔP with respect to the original detection.

A peculiar eclipsing pulsar in NGC 6397

NGC 6397 is one of the most promising targets for searching MSPs in GCs: in fact, it is one of the closest clusters, at a distance of $2.6 \text{ kpc} \pm 6\%$ [27], and probably has a collapsed core with hints of mass segregation [28]. It lies in fourth place in the list of GCs ranked according to central luminosity [24]. Moreover, it contains ~ 20 X-ray sources detected with *Chandra* within $2'$ of the cluster center, 8 of which probably identified with CVs [29].

In this cluster we have discovered PSR J1740-5340, a binary MSP with a spin period of 3.65 ms [21]. It displays eclipses at 1.4 GHz for more than 40% of the orbital phase. This phenomenon is not uncommon (10 eclipsing systems containing a MSP are known [11,30-34]) and in the case of PSR B1744-24A [35] the eclipses show duration and irregularities similar to those of PSR J1740-5340. However this new system is 2 – 3 times wider (with an orbital separation of $\sim 6.5 R_{\odot}$) than any other known eclipsing pulsar binary, and has a heavier minimum mass for the companion ($> 0.19 M_{\odot}$) than any known eclipsing system. In addition, the radio signal exhibits striking irregularities (delays and intensity variations) over a wide range of orbital phases (see Figure 2), indicating that the MSP is orbiting within a large envelope of matter released from the companion with a high mass loss rate. These characteristics challenge the evaporation models from a degenerate companion, suggesting more likely that the companion is a bloated main-sequence star or the remnant of the star that spun up the MSP

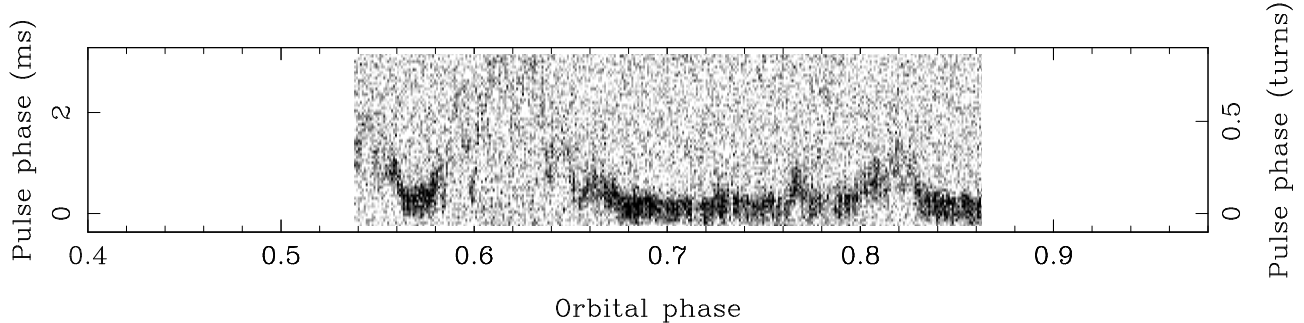


FIGURE 2. Greyscale plot of the signal intensity at 1.4 GHz as function of orbital phase (between phases 0.54 and 0.86) and pulsar phase for a 11 hr long observation of PSR J1740–5340 taken far from the nominal eclipse region (whose ingress is at orbital phase ~ 0.05 and egress at orbital phase ~ 0.45). The data are folded at constant period in sub-integrations lasting 120 s each. Darker regions correspond to higher signal intensity and thus roughly locate the average phase of the pulse in each sub-integration. The reference phase for the arrival of the pulses is set to 0. Upward shifts of the darker regions are a signature of delays occurring in the time of arrival of the pulses. The observation started at 15:02 UT on 2001 March 12 [34].

[34]. No millisecond pulsar with such peculiar companion is known to date. The detection of the pulsar in the X-ray band [29] and the probable optical identification of the companion [36] open also the possibility of extended follow-up observations which will probe the eclipse mechanism and the true nature of the companion in this very interesting system.

An isolated millisecond pulsar in NGC 6522

At a distance of 7.8 kpc [37] and with Galactic coordinates $l = 1.02^\circ$ and $b = -3.93^\circ$, NGC 6522 is one of the GCs located near the bulge of the Galaxy, only 600 pc away from the center. It is classified as core-collapsed [24], but the most interesting dynamical feature resides in its orbit, which recently ($\sim 2 \times 10^6$ yr ago) experienced a close encounter (at $\sim 400 - 500$ pc) with the Milky Way center. Hence, NGC 6522 could have experienced dynamical shocks due to the time-variable gravitational potential of both the bulge and the inner disk of the Galaxy [38].

So far in this survey, this is the only GC for which the only pulsar detected has been an isolated MSP, with a spin period of 7.1 ms [14]. PSR J1803–30 is in fact relatively strong and the previous surveys probably missed it due to its high $DM = 192 \text{ cm}^{-3}\text{pc}$.

A highly eccentric binary pulsar in NGC 6441

The most recent discovery occurred in the cluster NGC 6441. Its large distance (11.2 kpc) has been determined using RR Lyrae as calibrators [39]. It has a high central luminosity density but it is not classified as core-collapsed [24]. It hosts a bright low mass X-ray binary, XB 1746–371, whose optical companion has been likely identified at $6''$ from the cluster center [40]. It also contains one of the rare GC planetary nebulae, JaFu 2 [41].

Here we have found a binary pulsar, PSR J1750–37, which has the second largest DM ($233 \text{ cm}^{-3}\text{pc}$) and the longest spin period, 111.6 ms, among all the known GC pulsars (PSR B1718–19 has an even longer period, but its inclusion in NGC 6342 is unlikely [3]). After some months of timing, we have obtained an orbital solution (see Table 1) indicating that the system is large ($P_b = 17.3$ days), and in a highly eccentric orbit with $e = 0.71$ [14]. The minimum companion mass ($M_c^{\min} > 0.5$) suggests it could be a binary comprising a massive WD or a second NS.

CONCLUSIONS

After two years of observations and processing of data, we have discovered 12 new pulsars in 6 GCs, increasing the total sample of such pulsars by about 25%: there are now 54. We are timing all the new sources and within a few months will derive precise celestial coordinates for most of them. With these discoveries, we have also increased by about 50% the number of clusters (now 18) having at least one associated pulsar, and for which we have therefore also a good estimate of the DM. The consequent reduction in the number of unknown search parameters will make computationally feasible a future even deeper investigation of the pulsar content of these stellar systems, allowing a more reliable study of its dependence on other GC parameters such as mass, concentration, central stellar density, dynamic state and orbit in the Galaxy.

To date we have not obtained any pulsar detection in about 30 observed GCs. Our plan is to re-observe all of them. Indeed, the present experiment suggests that, besides sensitivity and powerful search algorithms, a key strategy in a search for GC-MSPs is to devote a large amount of observing time to each target. Scintillation in low DM clusters, long eclipses, and unfavorable orbital phases in the case of ultra-short binaries, might easily prevent detection during a single observation. For a subset of promising GCs we will also start a massive multidimensional coherent search in acceleration for a very large number of DM trials, exploiting the computing facilities available at the Cineca Supercomputing Center near Bologna.

Finally we will collect data for the ~ 20 GCs for which we have not yet performed observations: among them are the GCs in our list containing already known MSPs.

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